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Article

Environmental Impact Assessments of Integrated Food and Non-Food Production Systems in Italy and Denmark

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Abstract: Given the environmental footprints of the conventional agriculture, it is imperative to test and validate alternative production systems, with lower environmental impacts to mitigate and adapt our production systems. In this study, we identified six production systems, four in Italy and two in Denmark, to assess the environmental footprint for comparison among the production systems and additionally with conventional production systems. SimaPro 8.4 software was used to carry out the life cycle impact assessment. Among other indicators, three significantly important indicators, namely global warming potential, acidification, and eutrophication, were used as the proxy for life cycle impact assessment. In Italy, the production systems compared were silvopastoral, organic, traditional, and conventional olive production systems, whereas in Denmark, combined food and energy production system was compared with the conventional wheat production system. Among the six production systems, conventional wheat production system in Denmark accounted for highest global warming potential, acidification, and eutrophication. In Italy, global warming potential was highest in traditional agroforestry and lowest in the silvopastoral system whereas acidification and eutrophication were lowest in the traditional production system with high acidification effects from the silvopastoral system. In Italy, machinery use contributed the highest greenhouse gas emissions in silvopastoral and organic production systems, while the large contribution to greenhouse gas emissions from fertilizer was recorded in the traditional and conventional production systems. In Denmark, the combined food and energy system had lower environmental impacts compared to the conventional wheat production system according to the three indicators. For both systems in Denmark, the main contribution to greenhouse gas emission was due to fertilizer and manure application. The study showed that integrated food and non-food systems are more environmentally friendly and less polluting compared to the conventional wheat production system in Denmark with use of chemical fertilizers and irrigation. The study can contribute to informed decision making by the land managers and policy makers for promotion of environmentally friendly food and non-food production practices, to meet the European Union targets of providing biomass-based materials and energy to contribute to the bio-based economy in Europe and beyond.

Keywords: life cycle assessment; agroforestry; conventional wheat; olive trees; silvopastoral; global warming potential; acidification; eutrophication

1. Introduction

Due to the adverse impacts of the conventional arable production system on the environment, alternative production systems are required to maintain the multifunctional landscape of producing food, fodder, and energy. Agroforestry is one such alternative where crops and trees are integrated, in one field to produce a diversity of food, fodder, and bioenergy products and to mitigate and adapt to climate change. The Food and Agriculture Organization of the United Nations (FAO) have recognized the benefits of agroforestry systems to provide environmental, economic, and social benefits. FAO defines agroforestry systems to "include both traditional and modern land-use systems where trees are managed together with crops and/or animal production systems in agricultural settings" [1]. The term agroforestry thereby covers a range of production systems from natural grassland systems to intensively managed systems and so, the extent of agroforestry systems is difficult to estimate [2]. In spite of being common practice in tropical countries, the extent of agroforestry in Europe is rather limited [3] due to the intensification of farming systems, lack of integration of forest tress and agricultural land, and the absence of current adequate policies to promote agroforestry practices. Intensive farming has improved production with use of external inputs but has created many environmental concerns including loss of soil fertility and soil degradation [4]. In contrast, agroforestry with woody components can improve resource use in the aboveground and belowground to achieve ecological intensification.

Agroforestry is increasingly recognized as productive and environmentally friendly practice due to multifunctional roles in agronomic productivity and environmental performance of agroforestry systems. This calls for a quantitative assessment of environmental footprint in agroforestry systems. Life cycle assessment (LCA) is a robust tool for quantitative assessment of environmental footprint by taking account of the management inputs for comparison between production systems. Due to the diversity of agroforestry systems in Europe, environmental footprint of a specific agroforestry system under a particular environment can be very different depending on the inputs and the management intensity. In order to investigate the diverse agroforestry production systems in the study, Denmark was identified to represent Atlantic environmental zone and Italy was identified to represent Mediterranean environmental zone, representing two diverse environmental zones, for assessment of environmental footprints under different socioeconomic contexts.

Agroforestry systems in each country were identified as potential alternative production practice for comparison to the conventional arable crop production system. In Denmark, agriculture constitutes 72.6% of the land cover covering an area of 2,625,093 ha, while forestry covered only 9.5% in 2016 [5]. The integration of short rotation woody crops like willow and poplar into the arable fields (agroforestry) can contribute to microclimate effects like reduction of wind speed, reduced erosion [6], and mitigate nutrient leaching for protection of water quality [7] for sustainable production of food, fodder, and bioenergy.

In Italy, olive is one of the priority crops. Olive trees constitute the second most widespread crop, covering an area of 1,165,562 ha. It is the sixth most widespread crop in terms of production in Italy ranking third after Spain and Greece, the biggest producers of olives on a worldwide scale. Italy's share in global production was 10.9% (2,092,175 tonnes) in 2016 [8]. Olive orchards integrated with cereals are common agroforestry systems in the Mediterranean area to improve nutrient cycling and erosion control [9]. Hence, agroforestry systems play a significant role in production of olives and assessment of environmental footprint for comparison among the different management systems is necessary to identify the gaps in management for improvement.

LCA can be used to quantify the different environmental impacts of the olive production system to identify the management gaps in a production system [10–12]. LCA studies show that mineral fertilization contributes most to environmental impacts [13,14]. Irrigation also contributes considerably [12] for production of olive and irrigation is necessary for olive cultivation in the Mediterranean environmental zone. In Denmark, organic crop production and conventional production systems have carbon footprints of 2920 and 4474 kg CO_2-eq ha^{-1} yr^{-1}, respectively [15] whereas such carbon footprint assessments are lacking in Danish agroforestry systems.

The objective of the study was to carry out comparative LCA of four agroforestry systems with olive production in Italy and two production systems, specifically one agroforestry and one conventional wheat production system, in Denmark. Comparisons of environmental footprints were carried out among the production systems within the country and between Italy and Denmark.

2. Method

2.1. Study Site

The case studies are four agroforestry systems in Italy and two systems, specifically one agroforestry and one conventional wheat production system, in Denmark. The four agroforestry systems are olive trees under (i) silvopastoral agroforestry, (ii) organic agroforestry, (iii) traditional agroforestry, and (iv) conventional olive system, located in Orvieto in the Umbria region in Italy. The two production systems in Denmark are (v) a combined food and energy agroforestry system and (vi) a conventional wheat production system in Denmark.

The four production systems in Italy have olive trees as one of the components, while management and inputs differ among the systems depending on the production system as described below:

(i) Silvopastoral agroforestry system consists of 135 trees in 1.0 ha. Olive production is 3.6 t ha^{-1}, and natural grass pasture is present between the olive trees. A total of 177 sheep graze the pasture for 150 days a year, producing 0.33 kg dung in dry matter and 2.9 kg urine per day per sheep, with fertilization effects on the grass pasture. The trees were planted in 1956. While no synthetic fertilizer was used, biological copper was applied at 1.7 kg ha^{-1} [16].

(ii) Organic agroforestry system covered an area of 4.5 ha. The system has 200 trees ha^{-1} and olive yield is 2.2 t ha^{-1}. Naturally growing grass are present in between the trees, fertilizer application is 4.0 t ha^{-1} cow manure in dry matter, and no pesticides were used [16].

(iii) In traditional agroforestry, olive trees were planted in 1982. The yield is 7.05 t ha^{-1} olives with tree density of 529 trees ha^{-1}. The cultivation area was drip-irrigated and fertilized with olive prunings and olive pomace. Glyphosate was applied to control weeds [16].

(iv) Conventional olive system has planting density of 250–400 olive trees ha^{-1} with irrigation facility and practice mechanized harvesting of olives. The olive trees are fertilized with nitrogen (90–150 kg ha^{-1}), phosphorus (20–30 kg ha^{-1}), and potassium (70–120 kg ha^{-1}). Olive yield is estimated to be 4.5 t ha^{-1} with 300 trees ha^{-1} [17,18].

In Denmark, two production systems, namely a combined food and energy production agroforestry system and a conventional wheat production system, were investigated and the descriptions of the system are provided below:

(v) The combined food and energy system covers an area of 11.1 ha, of which 10.1 ha is cropped with barley, wheat, and clover in a four-year crop rotation and 1.0 ha of biofuel crops (mix of willow, hazelnut, and alder). The biofuel crops consist of four shelterbelts of short rotation woody crops, spatially placed at 50, 100, 150, and 200 m, forming alleys for the food and fodder crop production. The production yields were 5430 kg wheat ha^{-1}, 3750 barley kg ha^{-1}, 6700 kg clover ha^{-1}, and 4078 kg woodchips ha^{-1} annually [19,20].

(vi) Conventional wheat production systems relate to winter wheat production, which is sown in September or October and harvested the following year in August. A total of 50% of nitrogen (95 kg ha^{-1}), potassium (20 kg ha^{-1}), and phosphorus (60 kg ha^{-1}) is applied at the time of sowing and the remaining 50% of the nitrogen (95 kg ha^{-1}) is applied in the spring. Fungicides and herbicides are applied as per the standard practice at the experimental farm in Taastrup in Denmark. The details of the management and crop production are available from another study at the same experimental farm [19].

2.2. Data Collection

In Italy, the collection of data on each production system was obtained through interviews and surveys. A detailed interview was conducted with the respective farm mangers to obtain initial information on cultivation and management practices at each farm (Figure 1). Information on the description of the production systems, inputs used, and the management practices were gathered from the managers of the respective farms. Data was collected on animal and plant production, seed use, use of fertilizer or plant protection products, field size, irrigation, machinery use, and if any recent changes have been made to the farm practice within the past five years.

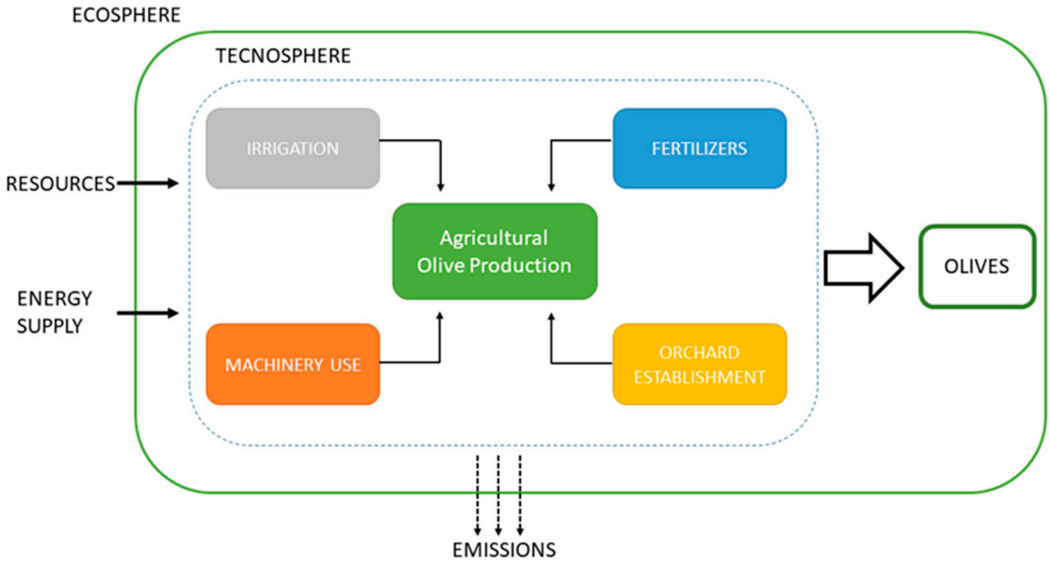

Figure 1. General flow diagram of olive production systems in Italy.

In Italy, three olive-based agroforestry systems were compared with a conventional olive production system in Italy, with a yield of 4300 kg ha^{-1} described in detail in the Ecoinvent database 3.3 [21]. The Ecoinvent database is the world's leading life cycle inventory (LCI) database, which provides well-documented data for thousands of products including agricultural processes.

In Denmark, input and production data were taken for the conventional wheat production system and combined food and energy system in Denmark from a previous study on the system [19]. Data collected included yields, field size, seed use, use of fertilizer or plant protection products, irrigation, machinery use, field preparation and, if any, recent changes made to the farm practice within the past five years (Figure 2). The combined food and energy system was compared with conventional wheat production system with a yield of 7341 kg wheat ha^{-1} and application of fertilizer, pesticides, and herbicides according to Danish standard practice as per the description provided under the study sites.

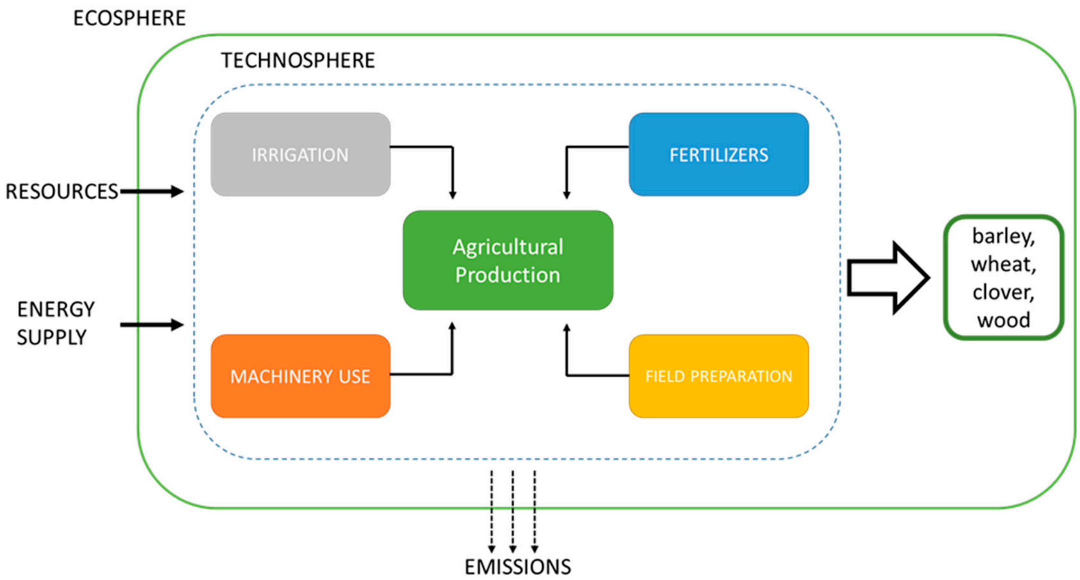

Figure 2. General flow diagram for the combined food and energy production system in Denmark.

2.3. Life Cycle Analysis

There is not one strictly defined methodology for conducting LCA analyses for agricultural production. However, according to the principles set out in ISO PN-EN 14040 [22], the full analysis should include the four phases of PN-EN ISO 14040 (goal and scope definition), PN-EN ISO 14041 (LCI-life cycle inventory), PN-EN ISO 14042 (LCIA-life cycle impact assessment), and PN-EN ISO 14043 (life cycle interpretation). The LCIA is the phase in which the environmental impact assessment (e.g., land use) of the products applies. Data obtained in the previous LCI phase were transformed into impact category indicators. This was done by selecting the impact category and impact indicators, assigning LCI results, and calculating the category indicator values. According to the methodology developed by the Society of Environmental and Chemical Sciences (SETAC), 14 environmental impact categories were taken into account in LCA, of which three were considered in this study, namely, global warming potential (GWP), acidification, and eutrophication.

LCA was done by applying SimaPro 8.4 software [23]. To calculate the emissions of inputs production for the Italian agroforestry systems, the Ecoinvent database 3.3 was used. Dinitrogen monoxide (N2O), ammonia (NH3), and nitric oxide (NO) were modelled based on methodology described in [24]. N_2O follows IPPC guidelines [25] Tier 1 for animal production and Tier 1 for crop production. NH_3 calculations were based on emission factors for NH_3, based on application of mineral N fertilizer and as a function of soil pH. NO is relatively of low importance compared to other sources, for that reason, simple emission factors were used [26]. Carbon dioxide (CO2) emissions after urea or lime application were calculated based on the factor (1.57 kg CO_2/kg Urea-N^{10} for urea and 44 kg CO_2/kg limestone or 48 kg CO_2/kg dolomite [26]. Irrigation quantity was calculated based on Methodological Guidelines for the Life Cycle Inventory of Agricultural Product [26] as consumed water for yield production (m^3 t^{-1}). The emissions related to pesticide use were not included due to low influence on calculated environmental impacts. The impacts of GWP, acidification, and eutrophication were calculated using the CML method [27]. The system boundary was cradle to olive farm gate, i.e., from the extraction of raw materials to the farm gate until the olives were harvested. For the Danish farm, the direct NO2-N and indirect NO2 emissions were calculated based on IPCC 2006 methodology [25], while the ReCiPe method [28] was applied to calculate the potential of GWP, acidification, and eutrophication. Due to the agroforestry systems producing different crops, the yields are not directly comparable. Hence, the yields were converted to monetary values based on the prices indicated: 0.49 \$ kg^{-1} wheat, 0.45 \$ kg^{-1} barley, 0.16 \$ kg^{-1} clover, and 0.14 \$ kg^{-1} woodchips [19].

3. Results

The estimated greenhouse gas (GHG) emissions from fertilizer and irrigation inputs are displayed in Table 1. The results showed that the main GHG emissions from the silvopastoral system was nitric oxide and ammonia, and from the organic systems, it was mainly nitric oxide. The main contribution of the traditional agroforestry system was CO_2 and the largest emission was from irrigation, which was only applied in the traditional agroforestry production system.

Table 1. Estimations of estimated greenhouse gas (GHG) emissions from four agroforestry systems in Italy and two production systems in Denmark. CFE: combined food and energy system.

Agricultural Practice	On Field Emissions	Methodology	Unit	Italy				Denmark	
				Silvo-Pastoral	Organic	Tradi-Tional	Conven-Tional	CFE	Conven-Tional
Fertilization	N_2O	EEA/EMEP (2013)	g kg^{-1}	0.00	0.50	0.31	0.4		
	CO_2	Nemecek (2014)	g kg^{-1}	0.00	0.00	31.18	5		
	NH_3	EEA/EMEP (2013)	g kg^{-1}	8.92	0.00	1.03	3		
	NO	EEA/EMEP (2013)	g kg^{-1}	12.35	34.20	0.24	0.7		
	Chemical N		kg ha^{-1}					0.00	190.00
	Manure N		kg ha^{-1}					16.00	35.20
	Crop residues N		kg ha^{-1}					0.00	0.00
	Direct NO_2-N N_2O	IPCC 2006	kg ha^{-1}					0.25	3.54
	Indirect (VOL.) NO_2-N N_2O	IPCC 2006	kg ha^{-1}					0.05	0.41
	Indirect (leaching) NO_2-N N_2O	IPCC 2006	kg ha^{-1}					0.06	0.80
Irrigation	H_2O	Nemecek (2014)	m^3	0.00	0.00	0.14			

In the combined food and energy production system in Denmark, GHG emissions emanated mainly from nitrogen (N) from the applied manure, with a small contribution from direct NO_2-N dinitrogen monoxide (N_2O). Much larger GHG contributions were recorded for conventional wheat production systems due to chemical fertilizer application.

The production system impacts on the environment are displayed in Table 2. In Italy, the highest global warming potential (GWP) was contributed by the traditional production systems, while silvopastoral systems exhibited the lowest GWP. The highest acidification and eutrophication effects originated in the silvopastoral system, whereas the lowest effects were recorded in the traditional system. In Denmark, GWP, acidification, and eutrophication were higher in the conventional wheat system than the combined food and energy system.

Table 2. Environmental impacts of the production systems. Greenhouse gas emissions from the Italian production systems are provided per weight (kg) of olive yield, while the unit of income ($) is used for the Danish production systems. GWP: global warming potential (GWP100a).

Impact Category	Unit	Italy				Denmark	
		Silvo-Pastoral	Organic	Tradi-Tional	Conventional Orchard	Combined Food and Energy	Conventional Wheat System
GWP	kg CO_2-eq. kg^{-1} yr^{-1}	0.166	0.266	0.655	0.388	0.615	4.922
Acidification	kg SO_2-eq. kg^{-1} yr^{-1}	0.022	0.018	0.007	0.008	1.290	6.844
Eutrophication	kg PO_4-eq. kg^{-1} yr^{-1}	0.005	0.005	0.002	0.004	2.957	20.446

Evident from Figure 3, the conventional and tradition production systems in Italy exhibited the highest adverse impacts on the environment due to fertilization. Silvopastoral and organic systems emissions mainly emanated from machinery use. GHG emissions due to orchard establishment were high on acidification and eutrophication impact categories in the silvopastoral system.

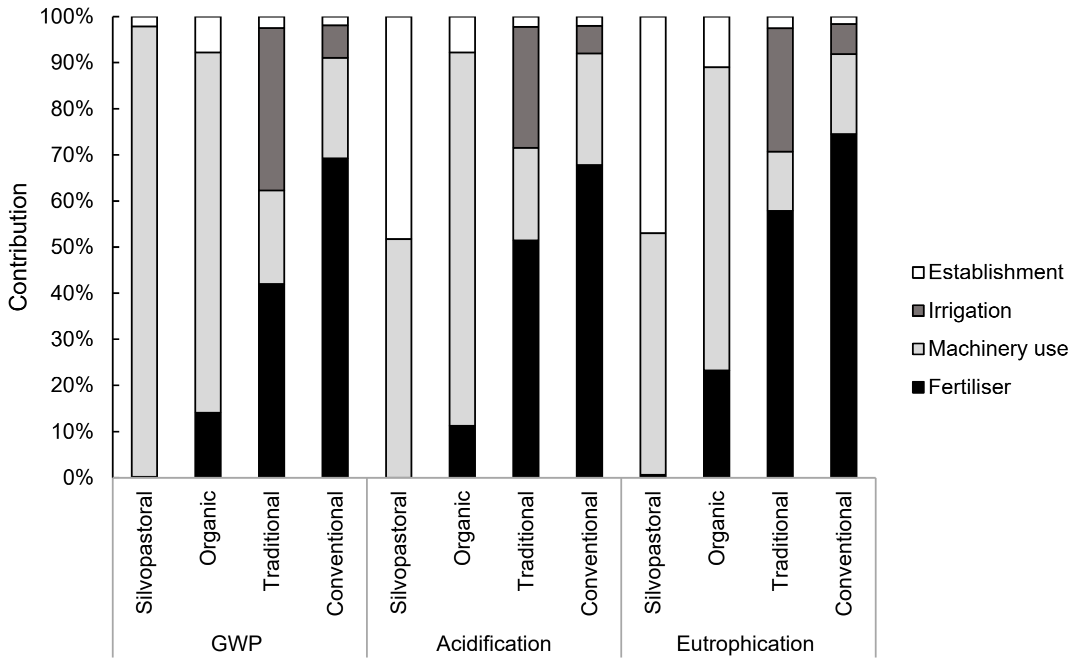

Figure 3. Percentage contribution from fertilizer, machinery use, irrigation, and orchard establishment on environmental impacts categories of global warming potential (GWP), acidification, and eutrophication for four Italian production systems.

Figure 4 shows that the application of fertilizer and manure had the greatest GHG emission contribution on GWP, acidification, and eutrophication for the conventional wheat and the combined food and energy system in Denmark. The second largest contributor to the GWP comes from machinery use, while seeding operation resulted in the second highest contribution to acidification and eutrophication in both production systems.

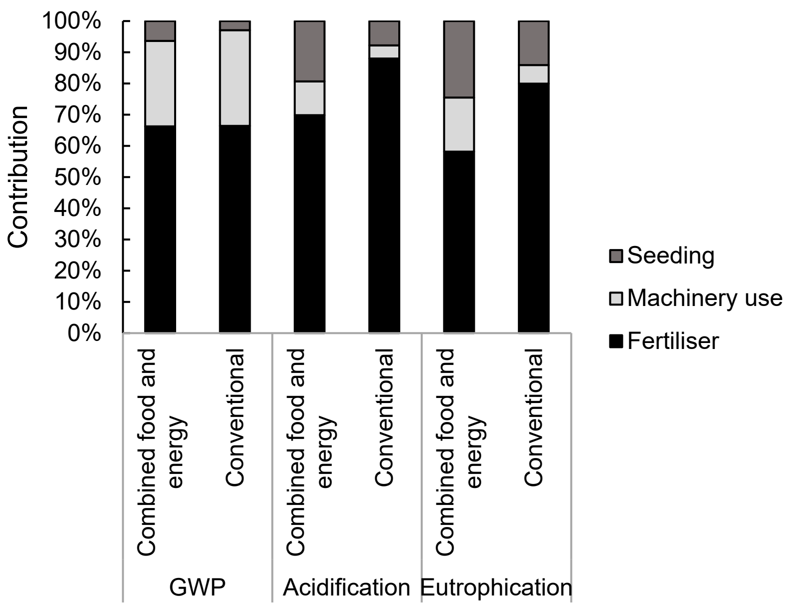

Figure 4. Percentage contribution from fertilizer, machinery use, and seeding on the environmental impact categories of global warming potential (GWP), acidification, and eutrophication for agroforestry and conventional production systems in Denmark.

The income from the diversity of produce in the combined food and energy systems in Denmark is presented in Table 3. Clover contributed to 49.1% of the total income, followed by wheat (30.5%) and barley (19.3%). The sale of willow woodchips amounted to only 1% of the total income.

Table 3. Income from the produce in the conventional wheat and combined food and energy production systems in Denmark.

Crop	Unit	Combined Food and Energy	Conventional	Share of Crop at Farm
Wheat	$ farm^{-1}	16,975.07		30.5
Barley	$ farm^{-1}	10,760.29		19.3
clover	$ farm^{-1}	27,342.72		49.1
Willow	$ farm^{-1}	570.89		1.0
Wheat	$ farm^{-1}		39,028.43	100.0
Total	$ farm^{-1}	55,648.96	39,028.43	

The environmental impacts of the two production systems in Denmark were estimated based on the income from each production system (Table 4). The combined food and energy system had a lower GWP, acidification, and eutrophication impact compared to the conventional wheat production system.

Table 4. Environmental impacts of the conventional wheat and combined food and energy production systems in Denmark. GWP: global warming potential (GWP100a).

Impact Category	Unit	Combined Food and Energy	Conventional
GWP	g CO_2-eq. \$$^{-1}$ yr^{-1}	123.89	1413.80
Acidification	g SO_2-eq. \$$^{-1}$ yr^{-1}	0.80	6.03
Eutrophication	g PO_4-eq. \$$^{-1}$ yr^{-1}	0.02	0.22

From the yield ha $^{-1}$ (kg ha^{-1}) and area (ha) for each of the Italian production systems, and from the income per farm (\$ farm^{-1}), yield per area and price of wheat (0.49 \$ kg^{-1}) for the Danish production systems, the GHG emission ha^{-1} (Table 5) was calculated based on the results presented in Table 2.

Table 5. GHG emissions ha^{-1} in production systems in Italy and Denmark. CFE: combined food and energy system.

Impact Category	Unit	Italy				Denmark	
		Silvo-Pastoral	Organic	Tradi-Tional	Conven-Tional	CFE	Conven-Tional
GWP	kg CO_2-eq. ha^{-1} yr^{-1}	606	585	4615	1669	3083	17,705
Acidification	kg SO_2-eq. ha^{-1} yr^{-1}	78	39	49	33	6467	24,618
Eutrophication	kg PO_4-eq. ha^{-1} yr^{-1}	18	11	16	18	14,825	73,618
Yield ha^{-1}	kg ha^{-1}	3640	2200	7050	4300		7341
Income ha^{-1}	\$ ha^{-1}					5013	3597
Area	ha	1.0	4.5	8.5		11.1	

4. Discussion

The comparison between specific types of production systems in two diverse environmental zones is challenging and cumbersome due to the differences in climate, soil, and management. Hence, a simple way to gain an initial overview of the environmental impacts of the studied production systems are presented in Table 5, with GHG emissions calculated per hectare. The data showed that the conventional wheat production system had the largest environmental impact ha^{-1} compared to other studied production systems in Denmark and Italy.

The environmental impacts of the six productions systems were calculated, based on three indicators of GWP, acidification, and eutrophication. Machinery use contributed the highest GHG contribution in the silvopastoral and organic production systems whereas fertilizer contributed the largest GHG in the traditional and conventional production systems in Italy.

The comparison of results with other studies was not straightforward as the farming systems and system boundaries varied between studies [10,11,14]. For Italy, the highest GWP calculated for the traditional farming system (Table 2) was mainly attributed to fertilizer (0.15 kg CO_2-eq.) and irrigation (0.13 kg CO_2-eq.). Romero-Gamez et al. [14] related this with CO2 and NO2 emissions to air caused by the manufacture and application of fertilizers to the cropping systems. In the present study, CO2 and N2O from fertilizer and machinery use were significant contributors to GHG emissions in the production systems. Romero-Gamez et al. [14] found that acidification was dominated by NH3 emissions to the air and those emissions were allocated to fertilizer production, in similarity to the present study, finding that fertilization and machinery use related to NH3 and NO had the highest impact on acidification.

Due to the diversity of products from the combined food and energy system, the environmental impacts were calculated based on the income from the two types of production systems in Denmark. Thus, acidification was found to be more than seven times higher for the conventional wheat production system in comparison to the combined food and energy system (Table 2) with the main impact from fertilizer related to NH3 and NO (Table 1). Likewise, the eutrophication and GWP in the conventional wheat system was 11.0 and 11.4 times higher, respectively, compared to the combined food and energy system, mainly caused by fertilizer use (Table 4). The study by Nemecek et al. [15] found increased environmental impacts by conventional production practice compared to organic agricultural practices by 1.5 times for GWP (4474 vs. 2920 kg CO_2-eq. ha^{-1} yr^{-1}), 1.4 times for acidification (88 vs. 61 kg SO_2-eq. ha^{-1} yr^{-1}), and 1.4 times for eutrophication (123 vs. 88 kg N-eq. ha^{-1} yr^{-1}). This supports the present study's findings of less environmental impacts from practices with reduced application of fertilizers and pesticides. While the GWP for the combined food and energy system is of similar magnitude to the organic system in Nemecek et al. [15], the GWP of the Swiss conventional wheat production system was much higher than the conventional wheat production system in the present study. Likewise, Knudsen et al. [29] found low GWP values of 2032-2599 kg CO_2-eq. ha^{-1} yr^{-1} for conventional wheat production system in Denmark in a four-year barley, potatoes, and winter wheat crop rotation including one year of either faba beans or grass-clover.

5. Conclusions

Among the six production systems, the conventional wheat production system in Denmark accounted for highest global warming potential, acidification, and eutrophication. In Italy, global warming potential was highest in traditional agroforestry and lowest in the silvopastoral system whereas acidification and eutrophication was lowest in the traditional production system with high acidification effects from the silvopastoral system. In Italy, machinery use contributed the highest greenhouse gas emissions in silvopastoral and organic production systems, while the large contribution to greenhouse gas emissions from fertilizer was recorded in the traditional and conventional production systems. In Denmark, the combined food and energy system was found to have lower environmental impacts compared to the conventional wheat production system according to the three indicators. For both systems in Denmark, the main contribution to greenhouse gas emission was due to fertilizer and manure application. Thus, the study demonstrated that the environmental footprint is dependent on the management intensity of the production system. The field-based evidence from the study can contribute to informed decision making by the land managers and policy makers for promotion of environmentally friendly food and non-food production practices to meet the European Union targets of providing biomass-based materials and energy for bio-based economy in Europe and beyond.

Author Contributions: A.P. and G.R. provided data on the Italian production systems, B.B.G. provided data on the Danish production systems, M.B. and K.Ż. conducted the data analysis. L.M.L. drafted the manuscript and B.B.G. and L.M.L revised and improved the scientific content of the manuscript. All authors have read and agreed to the published version of the manuscript.

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